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Landscapes Synthesis Achieved through Erosion and Deposition Process Simulation

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Abstract
This paper describes an original approach to terrain evolution in landscapes synthesis. In order to create some realistic landforms, we simulate geologically contrasted terrains and apply to them deterministic erosion processes. This allows us to relate the erosion on any point of the landsurface to local geological parameters. Any height field may be chosen as an initial topographic surface. Small perturbations may be introduced to avoid unpleasant regularities. A 3D model defines the geological parameters of each point according to its elevation. Our method is iterative: at each step, rock removal and possible alluvial deposition are computed at each point of the landsurface. The available erosion laws simulate mechanical erosion, chemical dissolution and alluvial deposition. At the end of each iteration, a new landsurface and the corresponding river network are created. Landsurfaces can be visualized at the final stage by two rendering algorithms including natural textures mapping. The stream network and the ridges may also be visualized.

Keywords: artificial landscapes modelling, geological phenomena simulation, landscapes rendering, natural textures.

1. Introduction

Generally speaking, artificial landscapes creation is concerned by producing both realistic and nice looking pictures of landforms. In contrast to previous approaches, we assume here that this can be obtained in a more efficient way through a modelling which takes into account geological parameters and laws. Our approach thus consists in using a geological description of the terrain and simulating its evolution.

The principle can be summed up as follows. We start with an initial landsurface that may be represented by any height field. Making use of a 3D geological model, definite geological parameters are assigned at each node. They are significant for further landscape evolution. This initial landsurface is then modified through an iterative method which simulates geological processes. At each iteration, the altitude of any point is changed by applying erosion and deposition laws. These laws simulate mechanical and chemical erosion as well as alluvial deposition according to local geological parameters. So, at each step, a new landsurface and the corresponding river network are created. At the final stage, two classical rendering algorithms are proposed for visualizing the resulting landform. The first one is a Z-buffer technique which takes into account the geological features of the landsurface in order to improve the realism of the rendering. The second choice consists in using a Ray tracing algorithm adapted to the terrain representation. Natural textures obtained by a spot noise method are mapped onto the surface. The river network and the ridges may also be visualized.

In this paper, we will first sum up previous works performed in landscapes synthesis. Afterwards, the terrain representation at geometrical and lithological level and the different geological processes will be detailed. We will present next the rendering algorithms and especially, the method for creating natural textures and for visualizing the stream network and the ridges. Finally, we will comment the resulting landscapes and conclude with further possible work.

2. Previous work

Creating synthetic images of landscapes usually involves two distinct procedures: modelling and rendering. A first approach of the problem consists in a procedural method using simple primitives texture mapping. It has been proposed by Marshall et al. [11] who used some linear primitives as initial surfaces and by Gardner [7] who used quadrics. In both methods, the resulting valleys do not really lookvery realistic since they are outlined by texture discontinuities at surface intersections. A second possible approach for creating authentic mountains uses well-known and efficient fractal techniques [10, 4, 12]. The resulting landscapes show accurate details and great realism but also a self-similarity character which is never observed in nature. In fact, different erosive processes operating on geologically ordered ground heterogeneities induce more various landforms.

During the last decade, some models have also been developed by geomorphologists. They mostly result in 2D erosion simulation and fall into two broad categories: analytic models [5] and simulation models [1, 9]. In fact, both of them first intend to check geomorphological theories. These models use erosive laws, including few transport equations and mass balance calculations on surface morphology [9,2]. The global erosion simulations are singular and operate on homogeneous geology [1]. There is no particular refinement in the visualization of the resulting landsurfaces.

Recently, landscapes modelling have been performed by trying to reproduce some actual geomorphological characteristics. Kelley et al. [8], for instance, created terrains by first generating a stream network, adding successive tributaries according to a mass transfer law. The landform is then created by computing elevations starting from the network and by fitting the final surface. The method provides a rather efficient way to model hydraulic erosion but produces some inconsistences between the fractal river network and the surface under tension. So, discrepancies between drainage basin and stream paths may appear. Musgrave et al. [13] proposed another simulation model of simple hydraulic erosion and thermal weathering operating on a fractal height field. He creates a drainage network and valleys with talus slopes at their feet. A third method is proposed by Arques and Janey [3] who produce artificial landscapes and associated stream network by modelling a planar map in which a fixed river network is introduced as a binary tree.

We may notice however, that, in contrast to the approach that will be proposed in the present paper, none of these recent models takes any account of possible geological heterogeneities of the ground and of the differential erosion that would result.

3. Simulation of erosion and deposition processes

3.1 Terrain representation

A classical method to represent terrains is to use an height field. This representation is especially suitable for topologic definition of our landsurface. For instance, it allows to use some DMA *(Digital Mapping Agency)* files as initial landsurfaces. Furthermore, geological parameters may be easily associated to the elevation map by means of a 3D geological model. By this way, a different lithology may be defined at each node.

Geometrical level The landsurfaces are described by means of a square or hexagonal height field. Each point of the grid has four or six equally distant neighbours. The use of an hexagonal grid is easy and makes the representation more accurate since each point has a greater number of neighbours. The dimension of the surface is specified by the number of points and by the distance between two neighbouring nodes of the grid. This distance is defined as the average width of a stream (in nature, about ten meters). This definition supposes that the creation of a stream is not possible between two neighbouring points. On the other hand, some areas of the surface can be represented at different levels of detail by modifying the mesh size. This representation allows to improve the efficiency of the process simulation.

No particular shape is imposed to the initial surfaces which could even be entirely flat. In fact, we usually select an inclined plane that we disturb by a slight altitude perturbation in order to create few irregularities. These modifications allow to start the erosion process more quickly and to create a definite direction of flow. They also avoid to obtain unpleasant symmetries when geological differences between neighbouring points are small. However, the transformation of the initial landsurface into hills and valleys will basically result from differential erosion connected with geological heterogeneities.

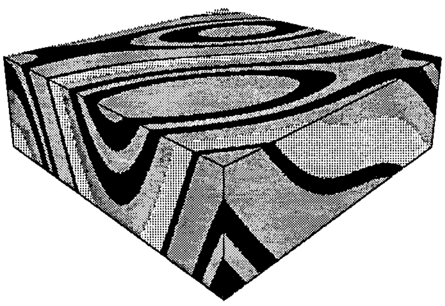
Lithological level The lithological characteristics of ground and bedrock have been simulated so that appropriate erosion laws may be applied during the iteration process. We assume that geology consists in layered rocks that may have been deformed by various folds and faults. Folds and faults are considered to be both cylindrical deformations; folds respect the strata pile continuity while faults introduce local discontinuities of elevation.

A geometrical model of geologically differential strata can be created, assuming naturally that each layer has different properties with respect to erosion. We will shortly sum up the main properties of the geological model that we use and which is issued from a previous work [14].

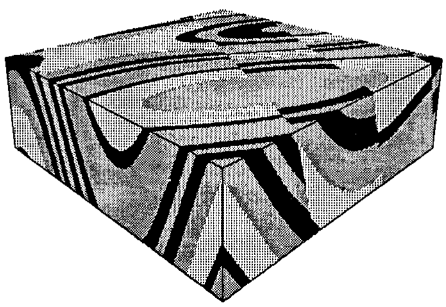
Individual folds and faults are simulated by a geometrical transformation which is applied to the model. Such a transformation specifies the deformation of each point of the geological structure. A global deformation is obtained by the concatenation of such elementary deformations. It is applied to an initial pile of horizontal strata and allows to create a full geometrical model of deformed terrains.

An elementary deformation results from the slipping of numerous planes (which are different from the original layers), with respect to one another along a definite direction. The magnitude of the offset between the various planes is specified by a profile function $f(x)$. Such a transformation thus associates at each point $M(x, y, z)$ a transformed point $M'(x, y, z + f(x))$. The profile function f defines the shape of the simulated deformation. It may be specified manually or with the help of a mathematical function: a sine function represents a fold, a staircase function a fault, an oblique line a tilt of strata.

This stratification defines a virtual 3D model, which is commonly visualized by a block-diagram where each layer is differencied by a colour (figure 1). The number and the thicknesses of the strata may be modified. The model allows to determine the lithological nature of any point of the landsurface.



(a)



(b)

Figure 1: *Block-diagram representations: (a) with two fold phases, (b) with two fold and one faultphases*

3.2 Geological parameters

Each point of the height field belongs to a given layer of the 3D model. In order to determine this layer, we calculate, from the actual location of the point, its different positions by cancelling the various deformations, in reverse order, one after the other. At the end of the process, we obtain the location of the point within the chosen stratification and we thus associate the corresponding lithology. An altitude lowering of one particular point of the landsurface may induce a change of its geological nature, since it corresponds to a modification of the location of the point io the 3D model.

Each layer has four parameters which quantify its geological behaviour with respect to erosion and deposition processes: rock softness (K_d), ability to chemical dissolution (K_c), permeability (K_f) and vegetal cover (K_v). Table 1 shows some examples of coefficients values for common strata. All these values range from 0 to 1. Alluvials have the same coefficients as river sands.

Stratum	Coefficients		
	K_d	K_f	K_c
Clay	0.90	0.10	0.30
Quartzite	0.10	0.30	0.30
Limestone	0.30	0.50	0.95
River sand	0.80	0.50	0.30
Granite	0.50	0.75	0.30

Table 1: *Geological parameters values*

For the representation of the vegetal cover (K_v coefficient), we propose the following rules:

- $K_v = 0$
  - for every point whose altitude is greater than or equal to the snow level,
  - for any slope $\geq 60^o$ (where vegetal cover virtually does not exist),
  - for all points which belong to river beds (these ones are defined according to the water height present at each point).
- $K_v = constant$ for any slope $\leq 30^o$.
- K_v is a linear function of the slope for values range from 30° to 60°.

3.3 Geological processes

Many erosion and deposition processes operating on the landsurface depend on various agents: rain water, ice and glaciers, wind... In the present paper, we only consider those processes that depend on running and infiltrated water.

The erosion and deposition processes may be viewed in the following way:

- each node of the grid receives the same quantity of rain water;
- part of this water is held by the vegetation and evaporated;
- the rest gets to the ground and is split into running water and infiltrated water according to the slope and to geological characteristics;
- the running water flows down and removes some rock detritals *(mechanical erosion);* this removal contributes to a lowering of the altitude which is added to the lowering resulting from gravity creep (i.e. slow terrain movement in the slope direction);
- the infiltrated water percolates through the soil and partly dissolves underground rocks *(chemical dissolution);*
- when the proportion of detritals carried by running water exceeds the stream capacity, the excess is deposited as alluvials along the slopes or in the basins *(sedimentation).*

The computation process through iterations : at each stage, the above mentioned processes are performed from point to point, from upstream to downstream. They allow to compute the new altitude of each point and, consequently, to produce a new landsurface.

We assume that the flow of running water coming to any point of the landsurface is entirely directed towards its lowest neighbour. Running water cannot come from low points of the model having no lower neighbours. Such points are not subject to erosion but only to alluvial deposition. This deposition will increase their altitudes so that, at a next iteration, some of them may be transformed into ordinary points. Closed basins are thus likely to disappear after a few iterations. Besides, when all the neighbours of a point have the same altitude (it is the case of a plateau), the flow direction is arbitrarily chosen.

At each stage, all the flow paths form the stream network which can be considered as a graph. Such a representation allows to examine all the points that are located upstream of a particular point before considering this point itself.

The following laws are issued from simplified geomorphological theories [5]. They are quantified with reference to the grid describing the landsurface. During one erosive cycle, each of these processes induces variations of the altitude of the nodes. The new landsurface morphology thus results from the balance between these laws. No accurate mass balance is computed; the total amount of dissolved matter and the major part of the detritals are just drained out the model.

Gravity creep law We suppose that, at any point, gravity creep is proportional to slope magnitude and to rock softness. The small resulting landslip induces a lowering of the altitude z_g at the given point P. If P is not a low point, the elevation of its lowest neighbour is increased of the same quantity. This phenomenon modifies the elevations but does not produce detritals.

$$z_g = K_d \tan(\theta)$$

where K_d is the rock softness coefficient and θ represents the angle between the segment joining P to its lowest neighbour and the horizontal plane.

Law of detritus removal by running water The removal of rock fragments by running water wears away the landsurface. The quantity of detritals S produced at each point depends on the amount of running water coming from upstream and on the erosive coefficient proportional to K_d. The quantity q of running water resulting from rain water fallen on a particular point is:

$$q = [1 - (K_f + K_v)]W$$

and the quantity of detritals produced is given by:

$$S = \alpha K_d \tan(\theta) q$$

where q is the quantity of running water, W is the amount of rain water, K_f is the infiltration coefficient and K_v the vegetal cover coefficient.

At any point of a stream, the amount of detritals is computed according to the total running water, cumulating the whole running water coming from upstream. We must add to this quantity the total amount of the detritals produced upstream that has not been deposited as alluvials. The total amount of detritals at any point i of the stream is thus expressed by:

$$S^i = \alpha \sum_{j=1}^{i} K_d^j \tan(\theta^j) \sum_{k=1}^{j} q^k$$

where $\tan(\theta^j)$ represents the slope at point j and K_d^j is the rock softness coefficient at point j.

Taking the expression of q into account, we get the final formula:

$$S^i = \alpha W \sum_{j=1}^{i} K_d^j \tan(\theta^j) \left[j - \sum_{k=1}^{j} (K_f^k + K_v^k) \right]$$

This law induces a lowering $z_w = S^i$ of the altitude of point i. The amount of detritals S^i is supposed to have been put in suspension in the running water coming from i. It may be thus subject to alluvial deposition downstream according to the sedimentation law which will be emphasized below.

Chemical dissolution law. We consider that the amount of infiltrated water q' at each point depends on the local infiltration parameter K_f. So we have:

$$q' = K_f q$$

Matter dissolved may be expressed by:

$$z_c = \gamma K_c q'$$

where K_c is the coefficient of chemical dissolution and q' is the amount of infiltrated water at the given point. γ is a coefficient which allows to specify the importance of chemical dissolution with respect to mechanical erosion. The lowering induced by chemical dissolution is considered to be equal to z_g.

Alluvial deposition law. Alluvial deposition occurs when running water gets to a low point or when the amount of sediments exceeds the transport capacity of the stream. This last condition depends on the flow rate and thus on the local slope.
There is no sedimentation when $\frac{S}{q} \leq \frac{r}{\cos\phi}$.
Otherwise, we deposit at the point the height h_s of detritals which results in an increase z_d of the altitude of the point:

$$z_d = h_s = q \frac{r}{cos\phi}$$

and a quantity $S - h_s$ of sediments is carried down. ϕ is the angle between the vertical line and the normal to the surface at the point and r is a transport coefficient which estimates the proportion of deposited and suspended detritals.

Alluvial deposits correspond to a specific geologic layer which is superposed upon the initial 3D model. In case of basins, the model fills them as much as possible to prevent generating disconnected streams.

Cumulating all these laws provides the altitude change of each grid point. At each stage, the new altitude is given by:

$$z' = -z_g - z_w - z_c + z_d$$

4. Rendering

The rendering of the eroded landsurfaces is performed independently of the modelling process. Two hidden lines algorithms which include natural textures mapping and artificial visual effects are available. Both can take into account the differences in the level of detail of the landsurface representation and consequently, adjust the visualization.

4.1 Z-buffer algorithm

The first hidden lines algorithm chosen for the rendering is a z-buffer method. The shading process produces hilly landforms. So, in order to visualize the outlines of the landscape, a different shading is used on either side of the ridge lines. The ridges are defined as the lines connecting all the points which have no upstream antecedent.

The stream network may be visualized to improve the realistic appearance. Its creation starts from definite points of the graph. In fact, all the points of the surface belong to the stream network but only some of them are selected for the visualization. They correspond to the most important tributaries. All these tributaries are fitted by a spline technique and two triangles are created for each section between two points of the interpolation. The width of the triangles is calculated in proportion to the depth of the points in the graph. To avoid that these new triangles cut any triangle of the landsurface, the altitudes of the new vertices are calculated according to the elevations of the surface.

4.2 Ray tracing algorithm

The second technique for landscapes rendering corresponds to a ray tracing method using a rectangular array of height values for the terrain representation [6]. Such a method provides more visual effects than the above mentioned technique such as shadows and reflections of the sunlight from the snow and water surfaces.

The projection of each ray on plane z = 0 intersects all grid cells that can lead to an intersection point. The first intersection point encountered on a ray can be the good one. Otherwise, the grid cells relative to one ray can be incrementally computed with use of a modified Bresenham algorithm DDA. It allows to reduce the average number of ray/objects intersections. If the current position on a ray lies outside the box bounding the terrain, this ray is discarded. This is also true for secondary rays.

To find the intersection point I of a ray R with a surface cell (A, B, C, D), the following method is used (figure 2). The projected ray R' intersects the projected surface cell (A', C', B', D') in the points M' $(A'B')$ and N' $(C'D')$. Let P and Q be the points on AB and CD and M and N the points on R that project themselves on M' and N' If $z_M > z_P$ and $z_N < z_Q$, then the point I is given by the intersection of (MN) with (PQ).

This approach may also be applied for an hexagonal height field with use of the triangular description.

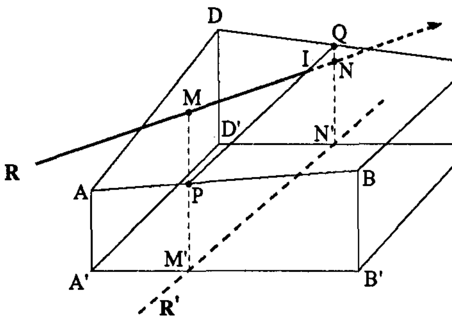


Figure 2: *Ray-surface intersection*

4.3 Textures

In order to improve the authenticity of the landscapes, natural textures are mapped onto the landsurfaces. The creation of these textures is based upon a spot noise method [15]. Spot noise is synthesized by addition of randomly weighted and positioned spots. This technique provides local control and is well-suited for texture design. The relationships between the features of the spot and the features of the texture are straightforward.

Thanks to these principles, various natural textures are created. Different sizes and shapes of spots are used to characterize various kinds of textures. These correspond to the different natural covers which exist in mountainous landscapes: grass lands, deciduous forests, conifer forests, alpine meadows, rocks and snow. These textures are mapped using classical principles which allow each of them to be assigned to a particular area according to exposition, slope and altitude. The difference between the textures of two neighbouring areas looks unpleasant. Hence, we reduce these visual effects by blending the textures at the boundaries of the concerned areas. In the final stage, blue atmospheric effect and water texture are added.

4.4 Resulting landscapes

For an accurate selection of the geological parameters, it is possible to compute surfaces which look like authentic landscapes such as those which may be observed in geologically contrasted mountainous areas. It appears that the results have a strong dependence on the geology of the area. Some morphological features induced by geology such as peaks, plateaus, valleys, hills, fault scarps are very conspicuous. These various structures are directly related to the nature of the bedrock and prove the efficiency of the simulation.

A small number of iterations allows easy creation of various landforms. Starting from one height field, we can obtain numerous landsurfaces by varying only the associated lithology. The resulting landsurfaces may be used as initial surfaces for another simulation. The stream network can also be easily visualized as it corresponds to the flow lines of running water which are already used within the erosion and deposition procedure.

Figures 3b&3c show the example of a landscape obtained after 50 and 100 iterations. The initial landsurface (figure 3a) is an hexagonal flat height field of 100 x 100 nodes, affected by a small perturbation. The geological model corresponds to layers of even but unequal thickness, which have contrasting physical properties. They are affected by two fold and by two fault deformation phases. All the above described erosion and deposition processes have been implemented in the simulation. The user time of this simulation computed on an HP-Apollo 94333 station is about four minutes for 50 steps including surface input/output. To retain clarity, the stream network is not visualized.

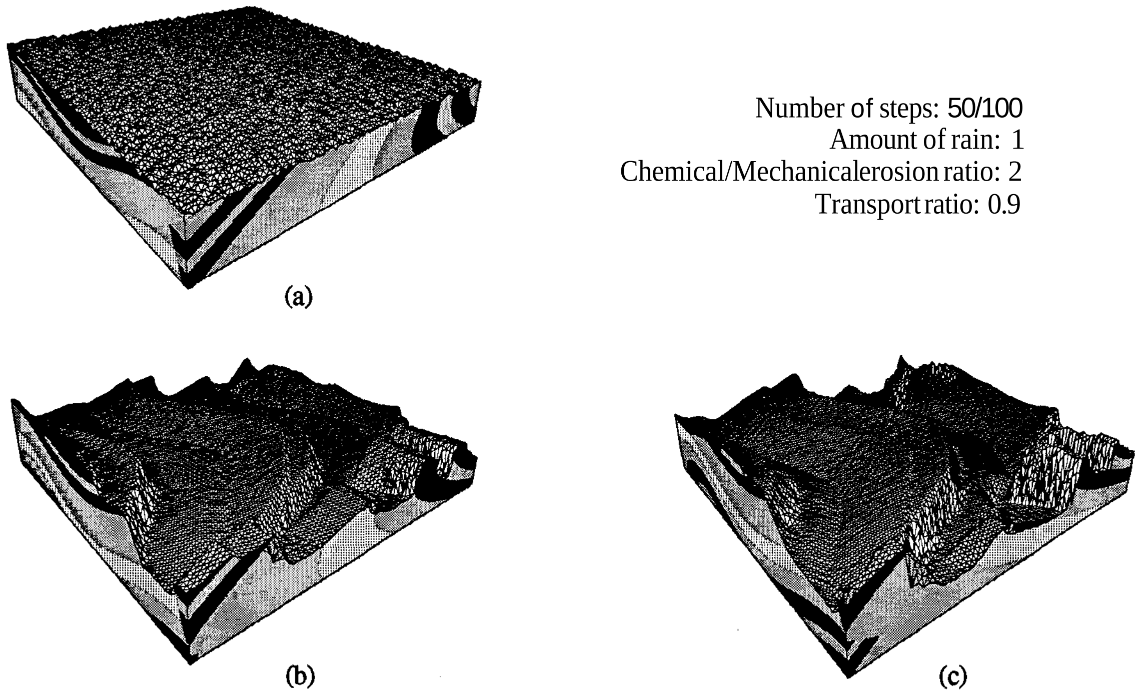


Figure 3: *(a) Initial landsurface, (b) Landsurface after 50 steps, (c) after 100 steps*

5. Conclusion

We have presented a new method for creating artificial landscapes which is based on geomorphologic theories. Unlike previous works, the simulation of erosive and deposit processes takes into account the geological features of the terrain, This model allows us to create some authentic landforms for mountainous regions with geological outlines and stream network. The results show the efficiency of the simulation, even with a small number of iterations. The flexibility of the different laws and the variety of the geological bedrocks provide numerous modelling possibilities.

Further work could be devoted to introduce other erosive processes such as wind and glacial erosion. These latter would enable us to obtain a fully realistic representation of many mountainous regions. However, they may be more difficult to simulate in a simple way than rain water processes. One could also think of using the results we have been presented to create computer animations of landscape evolutions.

Figures 4,5 and 6* present some landscapes issued from our simulation model. The visualization is realized with the Z-buffer technique including natural textures mapping, ridges and stream network representation.

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*** See page C–535 for Figures 4, 5 and 6.**